

EVALUATION OF INDIRECT TIRE PRESSURE MONITORING SYSTEMS USING DATA FROM NCSA'S TIRE PRESSURE SPECIAL STUDY

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ABSTRACT

In 2000, Congress passed the Transportation Recall Enhancement, Accountability, and Documentation (TREAD) Act. Section 13 of this Act directed the United States Department of Transportation to complete a rulemaking within one year. This rulemaking requires implementation of a warning system in new motor vehicles to indicate to the operator when a tire is significantly under-inflated.

In support of rulemaking activities mandated by Section 13 of the TREAD Act, the National Highway Traffic Safety Administration's National Center for Statistics and Analysis conducted the Tire Pressure Special Study (TPSS). The TPSS was designed to assess to what extent passenger vehicle operators are aware of the recommended tire pressures for their vehicles, the frequency and the means they use to measure their tire pressure, and how significantly the actual measured tire pressure deviated from the manufacturer's recommended tire pressure.

There are two types of Tire Pressure Monitoring Systems (TPMS), direct and indirect. Direct systems operate with a tire pressure sensor in each tire cavity while indirect systems monitor under-inflation by comparing characteristics of tires, e.g. comparing wheel speeds using the anti-lock braking system (ABS). This paper will discuss how the data from the TPSS were used to simulate the effectiveness of an indirect Tire Pressure Monitoring System.

BACKGROUND

Operating a vehicle with significantly under-inflated tires can result in a tire failure, such as instances of tread separation and blowouts, with the potential for loss of control of the vehicle. Under-inflated tires can also shorten tire life and increase fuel consumption.

The National Highway Traffic Safety Administration issued phase 1 of a rule in June 2002 requiring a Tire Pressure Monitoring System in new vehicles with a GVWR of 10,000 pounds or less, with a phase-in period for vehicles manufactured between November

1, 2003 and October 31, 2006. There are two options for compliance:

- TPMS must detect up to four tires under-inflated by 25% or more.
- TPMS must detect 1 tire under-inflated by 30% or more.

NHTSA is researching the options for compliance by examining the effectiveness of direct and indirect Tire Pressure Monitoring Systems. There are several items that NHTSA is preparing to provide in support of rulemaking for phase 2 of the rule:

- Real world data to determine the effectiveness of direct and indirect TPMS
- A survey of vehicle owners asking the following questions, among others, "Has your low tire pressure telltale ever illuminated? If so, how did you react to it?"
- Additional data on Tire Pressure Monitoring Systems

INTRODUCTION

At the time this paper is being written, the National Center for Statistics and Analysis (NCSA) is in the process of designing the real world study and securing approval from the Office of Management and Budget for the data collection forms. Tire pressure measurements will be taken on several thousand vehicles equipped with TPMS and an equal number of peer vehicles that are not equipped. Extents of under-inflation will be analyzed for each group and compared to determine the effectiveness of TPMS. The study is scheduled to begin in March 2003, and data collection will continue through September 2003. Analysis and results are to be presented prior to March 2004. Using these results, along with other relevant information, the Agency will decide upon a performance option for phase 2 with which the auto manufacturers would be required to comply beginning November 1, 2006

A previous study conducted by NHTSA (TPSS) can be used to provide additional data on the effectiveness of TPMS.

Many sources of information are needed to permit researchers to adequately measure the characteristics of the highway safety environment. NHTSA's NCSA operates a system of crash research teams that provide detailed nationally representative statistics on motor vehicle crashes and a database for evaluation of standards and countermeasures design.

In support of rulemaking activities, the Tire Pressure Special Study (TPSS) was conducted by NCSA in February 2001. The infrastructure of the National Automotive Sampling System (NASS) was used to provide a cadre of trained data collectors to minimize both cost and start-up time. The sample was comprised of 11,530 vehicles that visited gas stations for refueling during a two-week period in February between the hours of 8am and 5pm.

ANALYSIS AND RESULTS

Data were collected on over 11,000 vehicles during the TPSS. The body types were distributed among passenger cars and light trucks (including pickup trucks, vans, and sport utility vehicles). A limited number of these were equipped with Tire Pressure Monitoring systems (140 direct and 9 indirect).

Several methods for analysis were used. Before data were available on the TPMS equipped status of the vehicles in the TPSS, all of the passenger cars were used in a simulation to estimate effectiveness. Details of this simulation are in the following sections.

When sufficient data were available on the TPMS equipped status of vehicles from the TPSS, an analysis was performed comparing the under-inflation of the group of vehicles equipped with TPMS to the set of peer vehicles.

The variables of interest in determining the effectiveness of Tire Pressure Monitoring Systems are the recommended pressures for each vehicle and the measured pressures for each vehicle. These were compared to determine the extent of mis-inflation (mis-inflation is used to characterize the extent of under-inflation and/or over-inflation) for each tire and then for each vehicle as a whole. The data were used to determine both under-inflation and mis-inflation (over-inflation was included because indirect Tire Pressure Monitoring Systems do not distinguish between over and under-inflation).

Effectiveness of the system can be defined in several different ways. For the purpose of these analyses two definitions of effectiveness were determined.

1. Reducing the percent of vehicles in the equipped group, when compared with the peer vehicles, that have at least one tire under-inflated (or mis-inflated) past a certain threshold.
2. Reducing the average under-inflation (or mis-inflation) of the group of equipped vehicles when compared to the peer vehicles.

The thresholds for mis-inflation used were 25% and 30%. These correspond to the thresholds specified in phase 1 of the rule for each of the compliance options. The direct TPMS can meet the 25% threshold if any (or all) of the vehicle's tires are under-inflated. The direct and indirect TPMS must at least meet the 30% threshold if one of the vehicle's four tires is under-inflated.

Applying an Algorithm Simulating an Indirect TPMS to the TPSS Data

Because so few vehicles were equipped with TPMS in the sample in early 2001, it was necessary to examine the data in a variety of ways.

Research was done on TPMS to determine under what situations the warning lamp would activate to signal under-inflation. The indirect TPMS varies from manufacturer to manufacturer and can also change from model to model. Technology also progresses with time; therefore improved systems may be present now compared to those available in 1999.

To account for the many different types of TPMS, a general algorithm was developed by NHTSA and used in these analyses; the diagonal algorithm is similar to that used on most systems already being implemented. To account for other possibilities, the analyses also include a two-tire system. The algorithms were then combined to give the manufacturers the benefit of the doubt. If either of the two algorithms triggers a warning, then the vehicle was considered to be capable of triggering a warning. See the vehicle diagram in Figure 1, an example calculation is shown in the appendix.

- Diagonal Algorithm
 - o Most representative of what is currently on vehicles
 - o $((LF+RR)-(RF+LR))$
- Two-tire Algorithm
 - o $((LF-RF) \text{ or } (LR-RR))$
- Combination of Algorithms

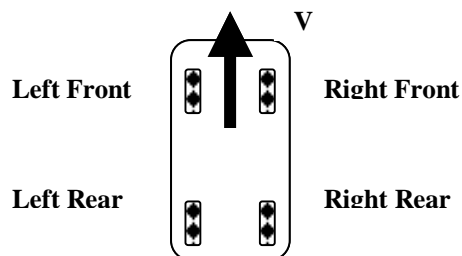


Figure 1. Vehicle Diagram

These algorithms were applied to the data for each vehicle in the TPSS and were used to determine whether or not an indirect TPMS present on that vehicle would have been capable of triggering a warning of under-inflation. The effectiveness of the indirect system was calculated by determining the number of truly under-inflated vehicles and finding the percentage of those that were capable of being detected by the algorithms.

Because the indirect TPMS functions by detecting differences between tires, it is impossible to detect under-inflation when all four tires are similarly

under-inflated. Data from the TPSS showed that 3% of passenger cars had all four tires under-inflated by 25% or more (Table 1). In addition, the indirect TPMS may have problems detecting under-inflation when more than one tire is under-inflated, depending upon the algorithm being used and the configuration of the under-inflated tires.

Table 2 shows some examples of possible scenarios of under-inflation. "P" is used to represent tires that are at placard pressure, while "L" is used to represent tires that are under-inflated by whatever threshold is chosen to represent significant under-inflation. The cells highlighted in red are those for which it is impossible to detect under-inflation given the algorithm used and the condition of the tires. There are countless combinations of both extent and location of under-inflation. In certain instances, a diagonal algorithm may have the capability to detect an under-inflation that a two-tire algorithm will not.

The results of the simulation take this into account and will show that the problem of detection is imminent for more than just 3% of passenger cars.

Table 1.
Percent of Vehicles in the TPSS with All Four Tires Improperly Inflated

Body Type	Mis-inflated by 25% or More	Under-inflated by 25% or More	Mis-inflated by 30% or More	Under-inflated by 30% or More
Passenger Cars	6	3	3	1
Light Trucks	7	4	3	2

Source: National Center for Statistics and Analysis, National Highway Traffic Safety Administration

Table 2.
Capability of Indirect TPMS to Detect Under-inflation Under Different Conditions

Front		Rear		Diagonal Algorithm	Two-tire Algorithm	Combination of Algorithms	Condition
Left	Right	Left	Right				
P	P	P	P	n/a	n/a	n/a	All at Placard
L	L	L	L				All Low
P	L	P	P				One Low
L	L	P	P				An Axle Low
P	L	P	L				A Side Low
P	L	L	P				Diagonal Low
L	P	L	L				Three Low
P=Placard Pressure		L=Low Pressure		Cannot Detect		Can Detect	

Source: National Center for Statistics and Analysis, National Highway Traffic Safety Administration

Results of Applying the Algorithm

Because the indirect TPMS does not distinguish between under and over-inflation, the data were analyzed by looking at the mis-inflation of the vehicle's tires. The absolute value of the difference between the recommended and the measured pressures was used. Thirty percent of the passenger cars and 28% of the light trucks in the TPSS had at least one tire mis-inflated past the threshold of 30%. Of those passenger cars, the diagonal algorithm was able to detect 38%, the two-tire algorithm was able to detect 43% and a combination of the two algorithms was able to detect 47%. Therefore, of the 30% of passenger cars with a mis-inflated tire, less than half of them would have received a warning (Results in Table 3).

Because the issue of interest to NHTSA is under-inflation, the data were also analyzed by looking at under-inflation only. Twenty percent of the passenger cars in the TPSS were under-inflated past the threshold of 30% (Table 4). Of those truly under-

inflated vehicles, the diagonal algorithm was able to detect 46%, the two-tire algorithm was able to detect 53% and a combination of the two algorithms was able to detect 53%. Therefore, of the 20% of passenger cars with an under-inflated tire, about half of them would have received a warning. The same was done with the group of light trucks. The results of the algorithms' capability to detect them can be seen in Table 3.

If the indirect TPMS were required to comply with the 25% option, the percentage of under-inflated vehicles that could be detected by the algorithm would be even lower. Even using the combination of algorithms, the system would only be effective for 48% of cars and 34% of light trucks that have at least one truly under-inflated tire. In all cases, under-inflation was more likely to be detected than mis-inflation. This may be due to the likelihood of vehicles with an over-inflation to have all four tires over-inflated, e.g. drivers filling their tires to the maximum pressure indicated on the tire sidewall.

Table 3.
Percent Effectiveness of Indirect TPMS in Detecting Improper inflation Using Different Algorithms

Algorithm Used	Mis-inflated by 25% or More	Under-inflated by 25% or More	Mis-inflated by 30% or More	Under-inflated by 30% or More
<i>Passenger Cars</i>				
Diagonal	33	39	38	46
Two-tire	36	44	43	53
Combination	40	48	47	53
<i>Light Trucks</i>				
Diagonal	25	28	31	37
Two-tire	25	30	32	40
Combination	30	34	37	44

Source: National Center for Statistics and Analysis, National Highway Traffic Safety Administration

Table 4.
Percent of Vehicles in the TPSS with at Least One Tire Improperly Inflated

Body Type	Mis-inflated by 25% or More	Under-inflated by 25% or More	Mis-inflated by 30% or More	Under-inflated by 30% or More
Passenger Cars	39	27	30	20
Light Trucks	39	29	28	20

Source: National Center for Statistics and Analysis, National Highway Traffic Safety Administration

Vehicles Losing Air Over Time

An important point to consider in requiring TPMS in all new vehicles is the interaction of the owners and drivers with the system. In the previous analysis two assumptions were made.

- The systems were calibrated properly for each vehicle.
- Upon receiving a warning from an indirect system, the driver would both know how to interpret it and know that he or she needs to check all four tires since the system does not specify which one is in need of attention.

Calibration is required for both direct and indirect TPMS. The systems must be “zeroed” when the tires are set to the vehicle manufacturer’s recommended pressure to insure that under-inflation is being detected relative to some desired number. There are many different ways to calibrate the system depending on each vehicle. For some indirect TPMS, calibration is a complicated procedure. For all indirect TPMS, calibration needs to be performed every time the tires are filled with air and every time the tires are changed or rotated.

There is a general concern that drivers who have vehicles equipped with TPMS may substitute reliance on that warning system for routine tire maintenance, a matter of particular concern for indirect TPMSs which may only provide a warning when one tire (not one or more tires) is significantly under-inflated.

A simulation was performed to see what would happen if drivers relied solely on the indirect TPMS to indicate when tires were under-inflated. Tires slowly leak air due to the permeability of rubber and due to changes in air temperature, leading to dangerous situations (because of the difficulty in detecting leaks) that are likely to occur when all four tires are under-inflated at the same time.

The simulation was done using a typical recommended tire pressure of 30psi. Leak down rates were selected randomly and ranged homogeneously from 0 to 1.5psi per month. Extent of under-inflation was monitored, as was period of time until a warning activated. It is possible to analyze the data in many ways, including determining the average amount of time a vehicle had an under-inflation until the warning was activated and the percentage of vehicles that would never receive a warning even if a tire was completely flat.

Results of the Simulation

For this simulation, effectiveness was defined as the percentage of vehicles for which the algorithm was capable of triggering a warning at the time at least one tire was truly under-inflated past the threshold.

Using the diagonal algorithm, the indirect TPMS was effective 17% of the time in detecting under-inflation in vehicles whose tires are normally losing air pressure over time. Using the combination of algorithms, the result was only slightly better, 26%.

Based on normal tire pressure loss, the average car will have at least one tire under-inflated by 30% in 6.5 months. With an indirect system, if drivers rely only on the TPMS to tell them when their tires are significantly low, the simulation estimates that the average driver won’t get a warning until 11.5 to 13 months because the difference in under-inflation between tires may be insufficient to trigger the algorithm. Thus, these drivers will be driving around with significantly low tire pressure almost half of the time. Using the diagonal algorithm, 28% of the vehicles would never trigger a warning, even if they had a completely flat tire. Of those that would eventually trigger a warning, the average extent of under-inflation when a warning was finally triggered was 14psi (46%). See Table 5 for the results of the simulation.

Table 5.
Performance of Indirect TPMS on Vehicles Slowly Losing Air Over Time

Algorithm Used	Effectiveness (Percent)	Never Alerts (Percent)	Average Under-inflation at Alert (in psi, percent in parentheses)	Average Time from True Under-inflation to Detection (months)
Diagonal	17	28	14 (46)	6.5
Combination	26	11	14 (46)	5

Source: National Center for Statistics and Analysis, National Highway Traffic Safety Administration

Tire Pressure Special Study Data

While simulations can indicate the possible effectiveness of indirect TPMS, it is necessary to consider both possibilities and functionality. If the systems are capable of detecting to a certain degree, what is more important is how they are used in the real world. Are they detecting under-inflation? Are drivers reacting, and if so, reacting properly?

Calibration is one issue that may pose an impediment to proper use of the indirect TPMS. From the TPSS, it was found that when people filled their tires, only 25% of them knew how to determine the proper inflation level for their tires. Twenty-seven percent of people used the value on the tire sidewall as their reference (this is the maximum inflation pressure for the tire, not the vehicle manufacturer's recommended pressure for the tires). Given these responses, the likelihood that the systems would be calibrated properly is an issue to consider.

Until the next tire pressure study begins, some of these questions will remain unanswered. In the meantime, data are available from the TPSS.

A limited number of vehicles measured in the TPSS were equipped with TPMS. The findings were not statistically significant, but the tire pressures of groups of vehicles equipped with TPMS were compared with the tire pressures of groups of vehicles not equipped with TPMS.

Because many factors can affect under-inflation, the group of vehicles not equipped was limited to those of the same body type and model years as the vehicles in the groups of equipped vehicles. The analyses were limited to passenger cars with p-metric tires in model years 1997 through 2001.

Results of the TPSS Data

There were very few vehicles equipped with Tire Pressure Monitoring Systems in the TPSS: 140 were equipped with indirect TPMS and 9 were equipped with direct TPMS. The set of peer vehicles included about 2,100 passenger cars.

The data were analyzed by looking at the recommended pressures of each vehicle and comparing them to each actual measured tire pressure. The same thresholds for under-inflation were used as before, 25% and 30%. Both mis-inflation and under-inflation were analyzed.

The average under-inflation of vehicles in the peer group was 14% under the recommended pressure, with 14% of the vehicles under-inflated by more than the threshold of 30% (Tables 6 and 7).

Table 6.
Average Deviation from Recommended Pressure of Vehicles in the TPSS by Equipped Status

TPMS Equipped Status	Average Mis-inflation (%)	Average Under-inflation (%)
Peer Vehicles	21	14
Vehicles with Indirect TPMS	16	7
Vehicles with Direct TPMS	13	11

Source: National Center for Statistics and Analysis, National Highway Traffic Safety Administration

Table 7 shows that of the 140 vehicles equipped with indirect TPMS, 14% (19 vehicles) were mis-inflated past the 30% threshold, about half of which were under-inflated and the other half over-inflated.

Of the 9 vehicles equipped with direct TPMS, none were mis-inflated past the 30% threshold (2 were

mis-inflated past the 25% threshold). The average under-inflation was 11%.

Due to the small number of vehicles equipped with TPMS, the results shown in these tables are preliminary.

Table 7.
Percent of Vehicles in the TPSS with at Least One Tire Improperly Inflated by Equipped Status

TPMS Equipped Status	Mis-inflated by 25% or More	Under-inflated by 25% or More	Mis-inflated by 30% or More	Under-inflated by 30% or More
Peer Vehicles	31	19	23	14
Vehicles with Indirect TPMS	17	7	14	6
Vehicles with Direct TPMS	22*	22*	0*	0*

*Note: n = 9 vehicles

Source: National Center for Statistics and Analysis, National Highway Traffic Safety Administration

CONCLUSIONS AND CURRENT STATUS REPORT

Based on the simulations and limited early data, NHTSA's assessment was that indirect TPMS are only capable of detecting half of existing under-inflations.

While the data in these analyses are very interesting, the findings are neither nationally representative and statistically significant, nor indicative of the real world performance of Tire Pressure Monitoring Systems.

Ideally, a real world study would be conducted a few years from now, when TPMS is present on more vehicles. In 2002, vehicles equipped with TPMS accounted for about 1% of all registered vehicles. Because under-inflation increases with the age of the tire (whether due to waning vehicle maintenance or increased permeability of the tire), it would be advantageous to wait until more vehicles equipped with TPMS are experiencing under-inflation, several years in the future. To expedite data availability in support of rulemaking activities, data collection will begin in March 2003 and continue through September 2003. Interviews will be conducted and vehicle measurements will be taken on vehicles that

are equipped with TPMS and those that are not. The effectiveness of direct and indirect TPMS will be calculated using the same techniques as the first analyses show in this paper. Results from the next study will be available in March 2004.

While new technology in indirect TPMS is allowing for finer thresholds of detection, the issue still exists of limited capabilities in detecting when more than one tire is under-inflated.

The presence of tire pressure monitoring systems should be used as a supplement to regular tire maintenance and care. Each tire, including the spare, should be checked monthly when cold and set to the recommended inflation pressure as specified in the vehicle placard and owner's manual.

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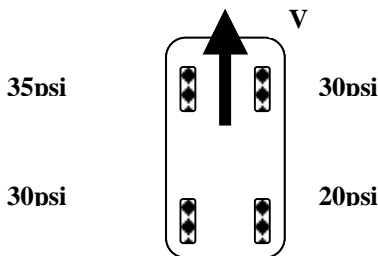
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APPENDIX

Example calculations using algorithms:



Diagonal Algorithm

$$(LF+RR)-(RF+LR) = (35+20)-(30+30) = -5$$

$$5/35 < 30\%$$

Will not detect

Two Tire Algorithm

(LF-RF) or (LR-RR)

$$(35-30) = 5$$

$$5/35 < 30\%$$

$$(30-20) = 10$$

$$10/30 > 30\%$$

Will detect

Combination of Algorithms

$$5/35 < 30\%$$

$$5/35 < 30\%$$

$$10/30 > 30\%$$

Will detect